OPTIMAL PULSE-MODULATOR DESIGN CRITERIA FOR PLASMA SOURCE ION IMPLANTERS

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ABSTRACT

This paper describes what are believed to be the required characteristics of a high-voltage modulator for efficient and optimal ion deposition from the "Plasma Source Ion Implantation" (PSII) process. The PSII process is a method to chemically or physically alter and enhance surface properties of objects by placing them in a weakly ionized plasma and pulsing the object with a high negative voltage. The attracted ions implant themselves and form chemical bonds or are interstitially mixed with the base material. Present industrial uses of implanted objects tends to be for limited-production, high-value-added items. Traditional implanting hardware uses the typical low-current (ma) semiconductor "raster scan" implanters. The targets must also be manipulated to maintain a surface normal to the ion beam. The PSII method can provide "bulk" equipment processing on a large industrial scale. For the first generation equipment, currents are scaled from milliamps to hundreds of amps, voltages to ~175kV, at kilohertz rep-rates, and high plasma ion densities.

When objects immersed in a plasma are pulsed, a space-charge layer of ions or "sheath" forms between the objects and the plasma. These ions "fall" across the applied potential and impact normally. As the ions are depleted from the plasma, the sheath expands away from the object. This results in a dynamic and time-dependent load capacitance and resistance. In addition, initial plasma-displacement currents help create an overall load characteristic that is difficult to electrically match efficiently. Plasma (gas) type, density, atomic species, gas mix, target (object) area and geometry, and secondary electron emission also affect load impedance. It would be advantageous to have one modulator system capable of efficiently processing various "product lines." Further problems also arise in that (particle) implant efficiency and product quality are also affected by the HV pulse waveform. A sharp rise time can bury the implant. Too slow a pulse rise or fall causes sputtering, drilling, or whiskers in addition to a reduced implant density. Optimal rise times coupled with the proper plasma density can provide: multiple improvements in deposited dose, a modified deposition density profile, and a smooth finished surface.

The resulting calculations from the plasma and network analysis codes will be presented in addition to experimental results that direct a solution toward the optimally efficient pulse power modulator system. The resulting pulse power modulator system outline and overall characteristic will also be presented in addition to suggested hardware configurations for future application.

THE PSII PROCESSES

Various organizations are using the Plasma Source Ion Implantation (PSII) process of Conrad [1,2,3]. As shown in Table 1, national and international groups are examining PSII and similar hybrid processes. Improvements in material hardness, fatigue life, wear, corrosion resistance, sliding friction, galling, and electrical and optical properties can be realized in just about any component, whether metal, ceramic, or plastic. Recent published efforts detailed results with cutting tools, stamping tools, draw dies, ball bearings, orthopedic devices, automotive, and aerospace components.

"Open" research summary results are most typically reviewed in the "PSII Newsletter" published by University of Wisconsin (UW). The UW newsletter has reviewed field testing of M-2 and A-2 implanted steels, among many other process results. Field tests of A-2 tool steel have shown improvements in life span by almost a factor of two (to 14 million hits) in the manufacture of aluminum cans. Field testing with M-2 pierce punches confirmed equally amazing improvements, with lifetime increases of better than 70 times. In addition to the typical gaseous implants (e.g., nitrogen for "nitriding"), two hybrid process have been developed: "Ion Beam Mixing" and "Ion Beam Enhanced Deposition" [4]. In these processes, material is deposited on a substrate by physical vapor deposition or chemical vapor deposition using the PSII procedure to integrate the coating into the substrate and/or additionally alter the coatings character. It is also known that metallic implants can also provide significant improvements to various substrate materials.

TABLE 1. PSII RESEARCH PROGRAMS

GROUP	STATUS
University of Tennessee	Operational
Northeastern University	Operational
General Motors Research Lab	Operational
Los Alamos National Lab	Operational
Hughes Research Lab	Operational
CSIRO/ANSTO-Australia	Operational
Varian Associates	Operational
Dalian University, Peoples Rep. of China	Operational
Harbin University, Peoples Rep. of China	Under Const.
Inst. Nuc. & Solid State Physics, Germany	Under Const.
University of Natal, South Africa	Operational
Applied Materials/UC-Berkeley/LBL	Operational
University of Wisconsin	Operational

PSII PHYSICS

When an object is immersed in a plasma and pulsed to a high negative voltage, the motion and displacement of the plasma electrons and ions partially determine the characteristic load impedance. Plasma type and density, object geometry, and secondary electron emission also significantly affect impedance. Second order effects can also (slightly) change the dynamic loading. These second order effects include the ionizing power, which additionally alters atomic species [5], and plasma density. The material composition of the "work piece" also has a marked and dramatic effect on load impedance, due to the work piece's secondary electron emission coefficient. For a given plasma density and type, various objects would present different dynamic loads. These various properties not only give rise to a time-dependent load characteristic but a multitude of process parameter characteristics. If one assumes an instantaneous voltage rise, the ion distribution evolves as shown in the figure 2. At time "zero," a neutral plasma surrounds the work piece. At time equal to "*t1*," Figure 2.2, the electrons from the plasma have been repelled in the vicinity of the work piece at a time interval (~6 ns) comparable to the inverse of the plasma electron frequency. At this point, the more massive ions have been "uncovered" to a distance called the "initial ion matrix sheath" [6]. The uncovered ions are then accelerated into the target, resulting in a large surge current, for a period related to the plasma ion frequency (~1-2μs). When the previous ion matrix has been significantly depleted and reaches an equilibrium with space-charge-limited Child-Langmuir flow (fig. 2.3), sheath expansion (fig 2.4) continues for the remainder of the pulse, maintaining current continuity laws [7]. The ion matrix current surge can be an order of magnitude greater than Child-Langmuir flow.

PLASMA DYNAMIC IMPEDANCE

The plasma dynamic resistance is a function determined by the space-charge limited conduction current, sheath expansion, and secondary electron emission [8]. The plasma sheath resistance for a 1-D planar geometry with a singly ionized plasma is given by

$$R_p = \frac{9}{4}\left(\frac{2}{e^3}\right)^{\frac{1}{2}} \frac{M^{\frac{1}{2}}V^{\frac{1}{2}}}{nA(1+\gamma)}\left(1+\frac{2}{3}\omega_{pi}t\right)^{\frac{2}{3}}, \quad (1)$$

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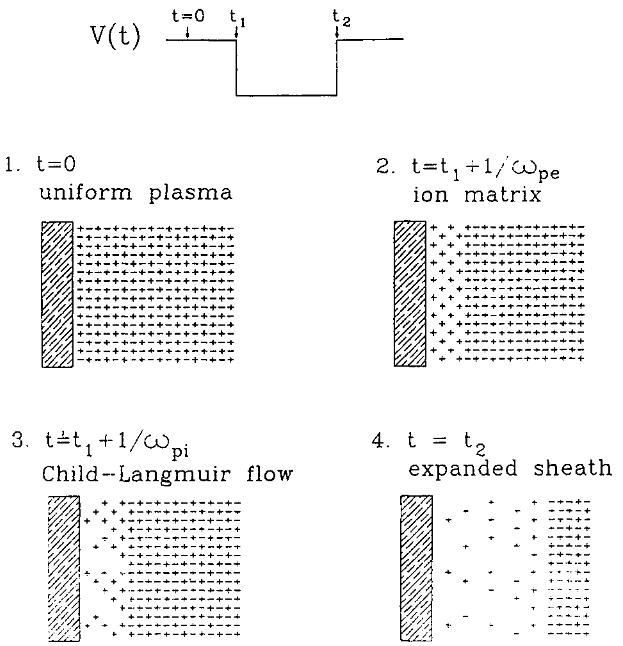
PLASMA EVOLUTION DURING PSII PULSE

FIGURE 2



where M is the ion mass, V is the sheath voltage, n is the plasma density, A is the implant area, ωpi the plasma ion frequency , and t is time. The secondary electron emission coefficient γ depends on ion energy and object composition and can be approximated for most cases of interest by

$$\gamma \approx (\beta V)^{\frac{1}{2}}, \tag{2}$$

where the coefficient ß depends on surface composition and ion implant species. The ion plasma frequency, dependent on ion density and mass is determined by

$$\omega_{pi} = \left(\frac{n_i e^2}{\epsilon_0 m_i}\right)^{\frac{1}{2}}. \tag{3}$$

Although the above equations are derived for planar geometry, they give an appreciation for the type of time varying load that can be expected for an actual 3-D object. A circuit simulation (planar geometry) of the load resistance as a function of time after space-charge-limited Child-Langmuir flow has been established is given figure 3. In this simulation the plasma density is 1E8/cc with a target area of 1E4 sq. cm. The secondary emission coefficient γ , is 10 (40kV) with a 25 amp maximum total current.

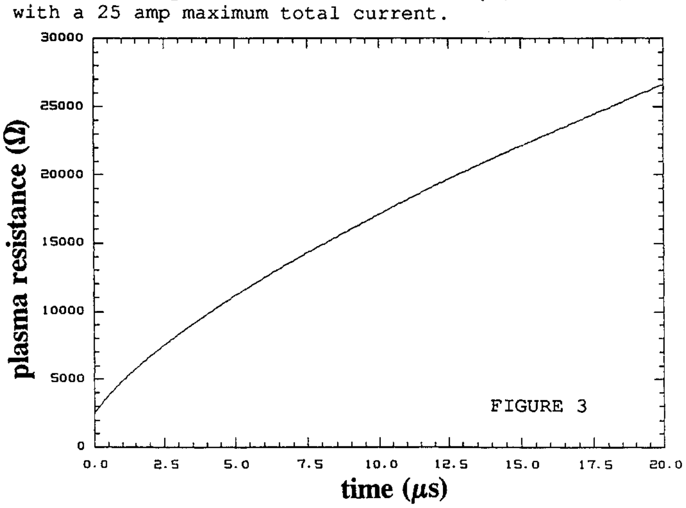


FIGURE 3

A 1-D particle-in-cell simulation (Figure 4) of the plasma implant current includes the large initial current surge from displacement current and the depletion of the ion matrix [9]. Simulations for three plasma densities are plotted for a 60 kV pulse voltage and a γ of 17 (60kV).

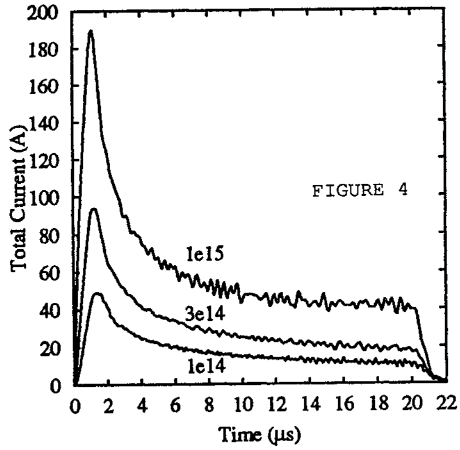


FIGURE 4

The plasma sheath capacitance is also a time varying effect dependent on applied voltage, particle density, and plasma ion frequency. The vacuum capacitance for a planar expanding sheath is given by

$$C_p = A\left(\frac{\epsilon_0 en}{2V}\right)^{\frac{1}{2}}\left(1+\frac{2}{3}\omega_{pi}t\right)^{-\frac{1}{3}} \tag{4}$$

In early time, the effective plasma sheath capacitance can be higher by a factor of two due to the uncovered ion matrix region. Typical load capacitance may vary from 500 to 1000 pF early in time to about 100 pF late in time. The modulator must also accommodate stray and transmission capacitance.

MODULATOR TIMING CHARACTERISTICS

Other factors that may affect modulator design criteria are the applied pulse width and repetition rate. The desired pulse width is determined by factors involving plasma ion density, vacuum chamber dimensions, and work piece size. The plasma ion density is determined by fill pressure and ionization power. A higher ion density results in a sheath that propagates at a slower rate. The difference in dimension between the work piece and vacuum chamber wall determines how much room is available for sheath expansion. Higher densities and large object features with greater object to vacuum wall spacing will permit longer pulse widths. Another consideration is the E-field profile across the sheath. Sharp objects do not like a sheath in close proximity (high plasma ion density), which can result in arcing and sputtering. It seems that for the present (and probably future) operational systems, a 20 μs pulse width is compatible with work piece features, ion density, and vacuum chamber dimensions. It is convenient that most high power switching devices are also compatible with this pulse width.

The maximum repetition rate (of the plasma) will be determined by the depleted sheath volume (a function of ion density, modulator current and pulse width) and rate at which the plasma ions can refill that depleted volume. The plasma ambipolar diffusion coefficient, which partially determines refill time, is a function of the ratio of electron to ion temperature [9]. The resultant calculation, a graph of ion refill time-constants for 3 energies, is given in Figure 5. A desirable implanter would have sheath expansions as small as possible (20 cm or less) consistent with conservative E-field intensities to limit breakdown probability. Maximum repetition rates could be realized in the 2 to 5 kHz regime. Higher ion densities and rep rates, coupled with the required higher switching currents (and <I>), all lend themselves to a higher production throughput rate.

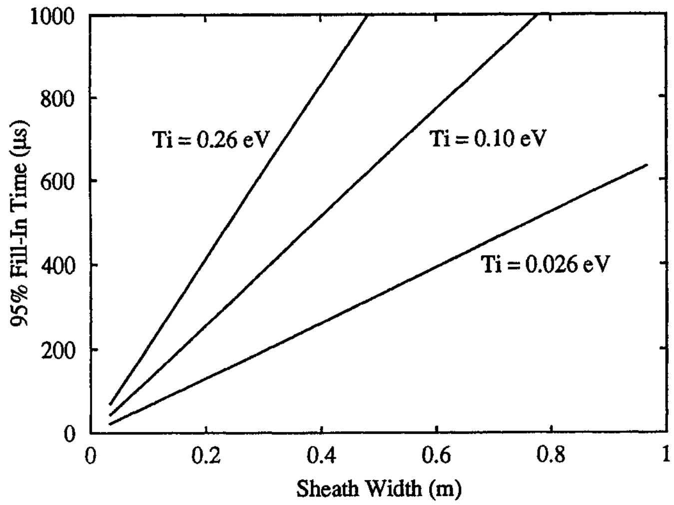


FIGURE 5: Plasma Refill Time (*Te*, 1eV)

MODULATOR DESIGN REQUIREMENTS

For a production-oriented industrial environment, reliability, amortized system cost, flexibility, and electrical efficiency are important considerations. To insure a reliable modulator system, a system design using an evolutionary hardware configuration can provide a modern design with components of characterized performance with predictable lifetimes and failure rates. Revolutionary hardware configurations must be approached cautiously and be carefully developed to determine actual operational and lifetime characteristics *before* utilization in a production environment. It is desirable for the modulator and high-voltage system to appear as reliable and transparent as the AC utility! The modulator and HV system should not require a fleet of technicians or constant surveillance! Due to the relatively high rep-rates and the required (long) component lifetimes for a reduced amortized system cost, pulse-rated components must be avoided. A typical pulse-forming network (PFN) capacitor has a 1E9 pulse lifetime, resulting in a failure in about twenty days at a 2 kHz rep-rate. A typical thyratron-switched PFN is questionable, not only because of the limited capacitor life but also because of the required impedance match for efficient operation. Any mismatch results in power being delivered to the end-of-line clipper. Swamping resistors used in an attempt to equalize the impedance variation impair efficiency. It is desirable for the modulator to be capable of varying pulse width, frequency, voltage, and current. This would provide a flexible design able to operate in various component processing modes and not be tied to a particular or fixed (obsolete?) PSII procedure. Component PSII process improvements can be made that would be transparent to the modulator and HV system. This type of flexibility can be provided by various classes of switch tubes. To maximize system efficiency, circuit topology must be examined carefully. For example, fault-current-limiting components can severely reduce system efficiency. A low-voltage design with a pulse transformer must be examined in detail due to increased primary RMS switching losses, in addition to transformer core losses. Vacuum switch tubes have the same relative voltage drop, whether at high voltage or low. It is the authors opinion that gridded switch tubes are questionable at the voltages and currents of interest (200A @ 50kV and above) because they are cumbersome, inefficient, circuit intensive, and often unreliable. High-current and high-voltage gridded switch tubes are large and typically require special fixtures and shrouds. They are not typically optimized for oil immersion, which reduces system size and external arc-down probability. Filament power can be large (many kW), and grid drive requirements can be troublesome with operation in negative resistance regimes. Special precautions must be utilized in order to protect the tube grids in the event of arc-down. Gridded tubes can lose hold-off ability due to whisker growth on the grid meshes after an arc-down.

Another important design consideration is fault modes and system protection. Systems that utilize series swamping resistors to limit fault currents also sacrifice efficiency. A typical and frequent fault (especially during initial "start-up") would be an arc-down of the object. Some switching devices have little current-limiting effect or may latch-up. Special design considerations or circuit topologies must be utilized to insure overall system safety. Hard-vacuum switch tubes have a large dynamic impedance that limits fault current to a similar value to that being switched. Regardless of the circuitry, energy must be removed (quickly) from the object to prevent whisker growth or drilling. If a hard-vacuum series switch is utilized, it may be simply turned off, without aborting the system. Another fault that must be considered is a "shoot-through" fault, a direct short through the switching network and the object to ground. Fault protection for this mode must include additional circuitry to quickly discharge any stored energy and remove primary (power supply) AC power. Follow-on current from the power supply short-circuit current (impedance-limited) must be considered, as turn-off time scales are significantly longer, and therefore, can impart a greater energy deposition to the object.

THE LOS ALAMOS MODULATOR

The Los Alamos modulator system is designed for large area implants (>1 sq.m) with voltages greater than 100 kV. Although presently operating at 60 kV, a new 150 kV power supply should be on-line within 1 year. The initial Los Alamos modulator and high-voltage system utilizes a more evolutionary design. We have chosen a modulator design using a pair of Litton L-3048 cross-field hollow-beam amplifier tubes as a series switch from a small capacitor bank. These hard-vacuum tubes are well characterized in military radar and particle accelerator service. Cataloged lifetimes have typically been in the 20,000 to 50,000 hour regimes. Important characteristics of the L-3048 (and related family) are its pentode like transfer curve, which limits any object arc-down current to that being switched. The input control element ("mod-anode") is high mu (gain) and virtually non-intercepting to the electron beam because of the tubes cross-field design. The cathode is shielded from high voltage (an internal arc-down will not strike the cathode) which permits the efficient use of oxide cathodes (75 w heater). The L-3048 has a design limit of 150 kV and a 30 Amp pulse current. Unfortunately, these amplifier tubes have a relatively high voltage drop (~10kV) and directly limit system efficiency to less than 90%. It could be a tube (of this design) that has been optimized for saturated switching service, could have a significantly lower voltage drop. The simplified block diagram of the initial Los Alamos modulator system is shown in Figure 6. The series switch tubes are in a "hot deck" configuration with power provided by an isolation transformer and control by fiber optic links. In a fault condition, diagnostic monitoring provides control signals that determine the appropriate action: shut off the switch tubes or shut down the power supply and switch tubes. Note that there are no fast crowbars, energy transfer is limited in the switch tube and object in a "shoot-through" fault condition by a 40Ω series resistance in the capacitor bank output (not shown). Because of the small capacitor bank size and power supply impedance, energy transfer is about 10 joules to both the object and switch tube, primarily from power supply follow-on current before SCR commutation, at most, 8.3 mS. The initial operation of the Los Alamos PSII system began in May '93, with a typical pulse waveform as shown in Figure 7. This oscilloscope photograph is a composite overlay at a 500 Hz rep rate. The implant current peaks at about 55 Amps and the voltage approaches 50 kV at the end of the pulse. The current limiting is due to the characteristic limit in the switch tubes at their given drive voltage. The current decay is due to plasma sheath expansion, which increases the dynamic impedance. The slight rise in voltage is due to the AC dynamic impedance of the switch tube coupled with the effect of the increasing plasma resistance. The poor fall time will be improved with the addition of a "tail biter" that discharges the object and transmission capacitance at the end of the pulse. The tail biter is not in our system but will be added in the future. Improvements in rise time can be realized with increased switching currents from hardware upgrades.

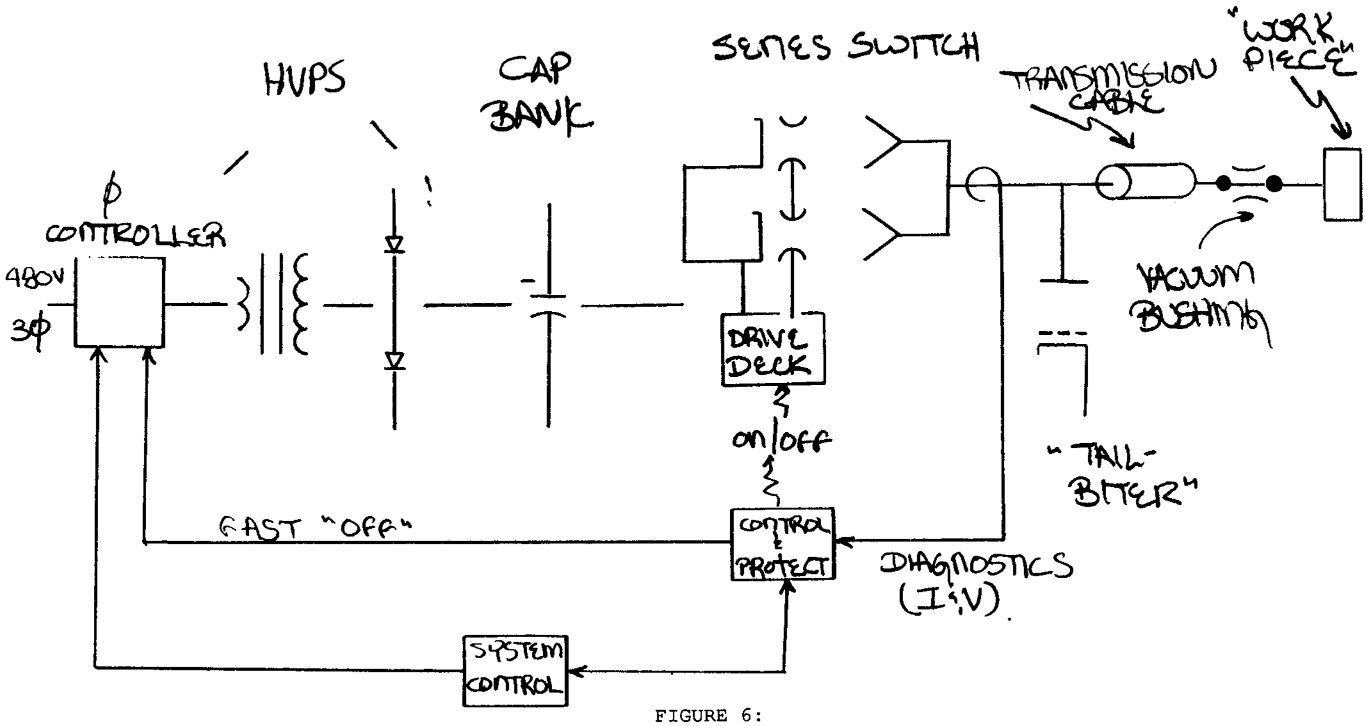


FIGURE 6:
Simplified Block Diagram of LANL PSII Modulator

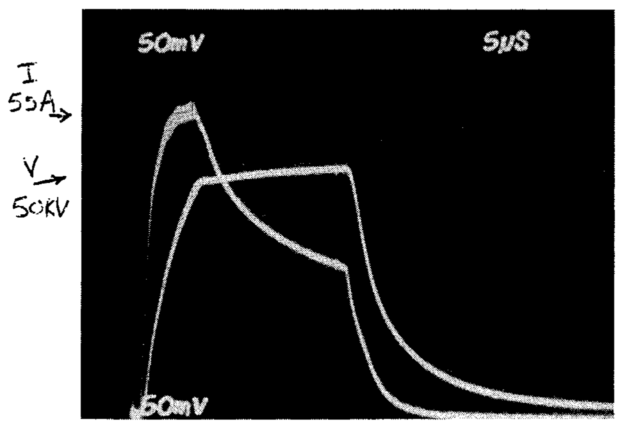


FIGURE 7:
Scope Photo of Modulator Output at 500 Hz Rep-Rate

CONCLUSION

The PSII process is an exciting field for the industrial use of pulse modulator technology. The modulator must operate over an extremely wide range of load impedance, from almost a short circuit early in time, to many thousands of ohms, late in time. Optimal design characteristics must not only examine various types of switching losses but also fault modes and follow-on currents. Overall circuit complexity must be minimized in addition to utilizing long-life components for lower amortized system cost. System reliability and operator resource and intervention requirements are also important to increase ease of use.

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